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Power allocation in NOMA with decoding order error of successive interference cancellation

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Abstract: In this paper, the decoding order error of successive interference cancellation (SIC) of multicarrier nonorthogonal multiple access (NOMA) due to the random walk of the users and position estimation deviation is considered in resource allocation. This factor extremely degrades the performance of NOMA in terms of sum rate and outage probability. Therefore, two optimal power allocation strategies for users are derived that maximize the sum rate and minimize the outage probability. The simulation results show that by considering the decoding order error in resource allocation, better performance can be achieved compared to the previous power allocation algorithms without considering this fact, which are a well-known water filling algorithm and a power allocation that maximizes the rate with minimum rate constraint.

Keywords: *Power allocation, NOMA, Successive interference cancellation, Convex optimization, decoding order error*

1 Introduction

NOMA is one of the powerful proposed multiple access techniques for the next generation of wireless communication systems. This technique improves the spectral efficiency and the number of supported users compared to the previous orthogonal multiple access techniques [1,2]. One of the NOMA methods is power domain NOMA, in which each subcarrier is assigned to more than one user with different power. The data of the assigned users to one subcarrier are sent by superposition coding. Thus, there are two new optimization variables, which are selecting assigned users for each subcarrier and the power of each, which are carefully studied in many literatures [3-5]

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At the receiver, the successive interference cancellation (SIC) is applied to the received signal to detect the data. In this approach, each receiver first decodes the data of users who have better channel gains and subtracts their data from the received signal. Then, it decodes its data. As a result, the decoding needs to follow the signal strength so as to make SIC succeed. One of the SIC decoding order selection methods is based on users' CSI [6]. However, the assumption of the availability of perfect CSI at the receiver is not realistic. In a practical wireless communication system, the mobility of the users and errors in the channel estimation lead to imperfect CSI. For example, the degradation of the NOMA performance due to the channel estimation error is studied in [7,8]. This imperfection is also recently considered in resource allocation, taking into account different objective functions in uplink or downlink [9-11]. However, imperfect CSI can lead to errors in the decoding order of SIC decoding, especially when receivers move at high speeds, like vehicles. In these cases, the receivers can not decode their data correctly, and the outage occurs. In this regard, the average sum rate and outage probability of NOMA with imperfect CSI are derived in [12] only based on the large-scale fading channel. Also, the resource allocation problem with imperfect CSI is solved under an outage probability constraint in [13]. The performance degradation due to the imperfect SIC is studied in different networks. The CSI-based power allocation in a cognitive radio network with the hybrid multiple access technology with imperfect SIC is studied in [14]. The framework for cross entropy in a millimeter wave channel is derived in [15]. In [15], the clustering, beamforming, and power allocation are investigated based on the imperfect SIC. The secrecy rate optimization in a cooperative network is optimized by considering imperfect SIC [16]. Recently, the imperfect SIC and hardware imperfection have been considered in spectral efficiency maximization for the network equipped with an intelligent reflector surface [17]. Based on these papers, one can conclude that imperfect SIC is very important to design a system with performance guarantees in the real world. However, none of them consider the random walk of users, which leads to the incorrect ordering of NOMA users.

In [18], the decoding order error probability is introduced, which is the probability that the decoding order based on the estimated distance is not identical to the actually CSI-based order. According to this definition, the closed-form expressions for average sum rate and outage probability are derived for the high SNR regime in [18]. The resource allocation for uplink and downlink is optimized by two different goals, which are sum rate maximization and outage probability minimization, only for a single-carrier NOMA system. This motivated us to propose the same resource allocation problem in a multicarrier NOMA system.

In this article, the multicarrier NOMA is considered, in which the random walk of the users may lead to the incorrect decoding order SIC. In this system, each subcarrier is occupied by two users and the total rate of users is formulated. After that, the total outage probability is studied. Based on derived formulas, the optimization problems are proposed in which the total rate and total outage probability are optimized in two problems. These problems are convex and are solved with the KKT approach. The results of optimization problems are compared with the resource allocation algorithm without considering the decoding order error of SIC. As expected, better performance is achieved by considering this practical imperfection of SIC in resource allocation compared to assuming perfect SIC. Based on the simulation results, considering the incorrect decoding order of SIC on the achievable rate in the low SNR regime is more important compared to the high SNR regime.

The remainder of this article is summarized as follows. First, the sum rate of all users is maximized under the maximum power constraint. Second, the average outage probability of all users is minimized under maximum power and minimum outage probability constraints.

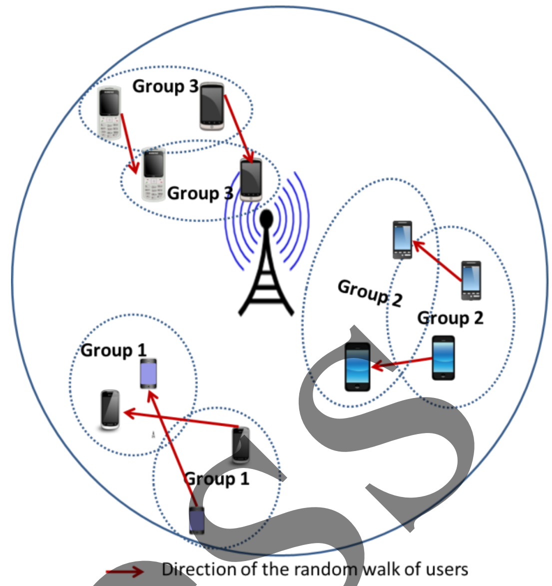

Fig 1. System model.

2 System Model

Consider a single-cell NOMA wireless network with one base station at the center of this cell and M users. The schematic of the system model by considering three groups is shown in Fig. 1. The random walk direction of users is shown in this figure. Note that only movement of users in group 1 leads to the disorder of NOMA users. Each two-user pair shares one subcarrier [19]. The users are paired based on the proposed algorithm in [20]. In [20], the users are sorted by the channel gains. The first user of this list is grouped with the last user of the list, and then they are deleted from the sorted list. This process is done until no user remains in the list. There are N' available subcarriers where $N' \geq N$. The channel gain of ith user to the BS at the allocated subcarrier to its pair is modeled as $g_i = h_i d_i^{-\alpha}$ where d_i is distance between ith user and the BS. In other words, the channel gain is modeled based on the combination of the large-scale path loss $d_i^{-\alpha}$ and a small-scale fading h_i. The users are distributed in the cell randomly and move in any direction at the time. The positions of the users are derived by time of arrival (TOA) measurement methods or the global positioning system (GPS) [21]. Assume that the position estimation deviations on the x and y axes are the random variables with a Gaussian distribution $N(0,\sigma^2)$ based on the central limit theorem [22]. The total allocated power to nth pair is denoted by ρ_n and the power scaling factor of the best user in this pair is represented by β_n.

Decoding order error probability is defined as the probability of the case where the decoding order based on the position estimation and CSI is not the same due to the random walk of users. This situation can be seen in the group 1 of Fig.1. This metric can be represented mathematically as

$$P_e^n = Pr\{d_{1n} < d_{2n}, |r_{1n}|^2 < |r_{2n}|^2\} + Pr\{d_{1n} > d_{2n}, |r_{1n}|^2 > |r_{2n}|^2\}, \tag{1}$$

where d_{in} and $|r_{in}|^2$, $i \in \{1,2\}$ are the position estimation and CSI of the ith user in the nth pair, respectively. By ignoring the fading and assuming $d_{1n} < d_{2n}$, the p_e^n can be simplified as

$$P_e^n = Pr\{d_{1n} > d_{2n}\} = \Sigma_{i=0}^{\infty}\Sigma_{j=0}^{\infty} P_{\lambda_{1n}\delta}(i) + P_{\lambda_{2n}\delta}(j) I_{i,j}, \tag{2}$$

where $I_{i,j} = 0.5^{i+j+2}\binom{i+j+1}{j} + F(1, i+j+2, j+2, 0.5)$,

$P_{\lambda_{in}}(k) = \frac{e^{-\lambda_{in}}\lambda_{in}^k}{k!}, k \geq 0$, $\lambda_{in} = d_{in}^2$, $\delta = \frac{1}{2\sigma_{ob}^2}$, σ_{ob} is position estimation deviation and F is a hypergeometric function. The average sum rate of the nth user's pair in the high SNR region can be approximated as [18]

$$R_{sum}^n \approx \log_2 \frac{\rho_n}{\lambda_{1n}} - P_e^n \log_2 \frac{\lambda_{2n}}{\lambda_{1n}} - \frac{C}{Ln2}, \tag{3}$$

where C is the Euler constant [23].

As a result, the average sum rate of all pairs of users calculated as follows

$$R_T = \sum_{n=1}^{N} R_{sum}^n. \tag{4}$$

Note that by considering (4) as an objective function, the vector of $\rho = \{\rho_1, ..., \rho_N\}$ is a variable of the resource allocation problem which is not in the single carrier NOMA [18].

In many applications, e.g., delay-sensitive communication, there is a minimum required rate denoted by R_0 or equivalently the minimum SNR threshold $\epsilon_0 = 2^{R_0} - 1$. When the instantaneous channel SNR, which is a function of channel gain, is lower than ϵ_0, the receiver can not decode its data and outage occurs. In NOMA, the outage occurs when each receiver can not decode its data or the data of the weaker users. Therefore, the common outage probability of the nth pair based on the decoding order error, can be calculated as [18]

$$P_{cop}^n = 1 - (1 - p_e^n)e^{-(\lambda_{2n}A_n + \lambda_{1n}\zeta_n)} - p_e^n e^{-(\lambda_{1n}A_n + \lambda_{2n}\zeta_n)}, \tag{5}$$

where $A_n = \frac{\epsilon_0}{\rho_n(\beta_n - (1-\beta_n)\epsilon_0)}$, $\beta_n - (1-\beta_n)\epsilon_0 > 0$, $B_n = \frac{\epsilon_0}{\rho_n(1-\beta_n)}$, $\varsigma_n = \max\{A_n, B_n\}$ and β_n is the larger power scaling factor of the nth pair. This probability can be approximated as

$$P_{cop,app}^n = 1 - e^{-(\lambda_{2n}A_n + \lambda_{1n}\zeta_n)}. \tag{6}$$

According to the [14], the optimum β_n for nth pair, which minimizes the approximated common outage probability, $P_{cop,app}^n$ is as follows

$$\beta_n = \frac{\sqrt{1+\epsilon_0}(\epsilon_0\lambda_{1n} - \lambda_{2n}) + \sqrt{\lambda_{1n}\lambda_{2n}}}{\sqrt{1+\epsilon_0}[\lambda_{1n}(1+\epsilon_0) - \lambda_{2n}]}, \tag{7}$$

which is not a function of total assigned power to the nth pair (ρ_n).

The average common outage probability of all pairs of users can be calculated as

$$P_{cop} = \frac{\sum_{n=1}^{N} P_{cop,app}^n}{N} = 1 - \frac{\sum_{n=1}^{N} e^{-(\lambda_{2n}A_n + \lambda_{1n}\zeta_n)}}{N}. \tag{8}$$

Note that A_n and ς_n are function of ρ_n. As a result, by considering (8) an objective function, the vector $\rho = \{\rho_1, ..., \rho_N\}$ is a variable of the resource allocation problem, which is a new variable compared to [18].

3 Power Allocation

In this section, the optimal total allocated power to each pair is derived by considering two different objective functions. First, the average sum rate of all pairs is maximized subject to the maximum total power constraint. Second, the common outage probability of all pairs is minimized by considering the maximum total power limitation.

3.1 Average Sum Rate Maximization

In this subsection, the optimal power allocation that maximizes the average sum rate of the network is derived. Note that, the rate of each pair based on Eq. (3), is independent of the power scaling factor of the two users in the pair. As a result, the variables of the resource allocation with the goal of sum rate maximization are only the total allocated power to each pair ρ_n, $n \in \{1, ..., N\}$. Based on the Eq. (3) and Eq. (4), the optimization problem is formulated as

$$\max_{\rho} \sum_{n=1}^{N} \log_2 \frac{\rho_n}{\lambda_{1n}} + C_n$$
$$s.t. \sum_{n=1}^{N} \rho_n \le P_{max} \quad (9)$$

where $P_{\max}$ is a maximum power limitation, and $C_n = -P_e \log_2 \frac{\lambda_{2n}}{\lambda_{1n}} - \frac{C}{Ln2}$ which is not a function of ρ_n. The resource allocation problem is a convex optimization problem. As a result, the Lagrangian multipliers method and KKT approach can be used for solving as follows,

$$L = \sum_{n=1}^{N} \log_2 \frac{\rho_n}{\lambda_{1n}} - \lambda(\sum_{n=1}^{N} \rho_n - P_{max}). \quad (10)$$

By taking the derivative of the above equation with respect to ρ_n and set it to zero, we have,

$$\frac{\partial L}{\partial \rho_n} = \frac{1}{\rho_n} - \lambda = 0, \quad (11)$$

which leads to $\rho_n = \frac{1}{\lambda}$. On the other hand, for $\lambda \neq 0$, this equality should be hold $\sum_{n=1}^{N} \rho_n = P_{max}$. As a result, $\lambda = \frac{N}{P_{max}}$ or equivalently $\rho_n = \frac{P_{max}}{N}$. Therefore, equal power is allocated to the pairs, which can be easily applied in the practical communication systems.

3.2 Average Common Outage Probability Minimization

In this subsection, the optimal power allocation of the users that minimizes the total outage probability is derived. The optimal power scaling factor between two users of the nth pair, which minimizes the outage probability of that pair can be calculated based on the Eq. (7). Note that in Eq. (7), A_n, B_n and ς_n are functions of $1/\rho_n$. As a result, $P_{cop,app}^{n} = 1 - e^{v_n/\rho_n}$ where $v_n = \lambda_{2n} \frac{\epsilon_0}{(\beta_n - (1-\beta_n)\epsilon_0)} + \lambda_{1n} \max\{\frac{\epsilon_0}{(1-\beta_n)}, \frac{\epsilon_0}{(\beta_n - (1-\beta_n)\epsilon_0)}\}$. Thus, v_n is independent of the total allocated power to the nth pair ρ_n. Thus, the total outage probability of a multiuser-multicarrier NOMA system based on Eq. (8) is as follows

$$P_{cop} = 1 - \frac{\sum_{n=1}^{N} e^{-(v_n/\rho_n)}}{N} \quad (12)$$

As a result, the optimization variables of this problem are the total allocated power to the pairs ($\rho_n, n \in \{1,...,\mathrm{N}\}$) as follows,

$$\min_{\rho} 1 - \frac{\sum_{n=1}^{N} e^{-(v_n/\rho_n)}}{N}$$
$$s.t. C_1 : \sum_{n=1}^{N} \rho_n \le P_{max}, \quad (13)$$
$$C_2 : \rho_n \ge \frac{v_n}{0.7}$$

where the second constraint (C_2) guarantees that the common outage probability of each pair of users is higher than 0.5. The second derivative of the objective function with respect to ρ_n is positive for $\rho_n \ge \frac{v_n}{2}$. The Hessian matrix of the objective function is a diagonal matrix in which the diameter values of the matrix are positive for the feasible region. Thus, the Hessian matrix is positive definite and the optimization problem is convex. Therefore, the Lagrangian multiplier and KKT approach can be applied to solve the problem as follows,

$$L = 1 - \sum_{n=1}^{N} \frac{e^{\frac{v_n}{\rho_n}}}{N} - \lambda(\sum_{n=1}^{N} \rho_n - P_{max}). \quad (14)$$

The optimum ρ_n should satisfy the following equality

$$\frac{\partial L}{\partial \rho_n} = \frac{v_n}{N \rho_n^2} e^{(\frac{-v_n}{\rho_n})} - \lambda = 0. \quad (15)$$

As a result,

$$\rho_n = \max\{-\frac{v_n}{2Ei(-0.5\sqrt{v_n \lambda N})}, \frac{v_n}{0.7}\}, \quad (16)$$

where $Ei(.)$ is the Lambert W function. Also, λ can be derived from

$$\sum_{n=1}^{N} \rho_n = P_{max}. \quad (17)$$

4 Simulation Results

In this section, numerical results show the performance of the proposed power allocation strategies. Assume a network with 20 users that are uniformly distributed in the square region 20x20. The base station is in the center of the region. The Rayleigh fading channel with channel path loss exponent 2 is considered for modeling the channel. The noise variance is set to -50 dbm. The results are averaged over 1000 Monte Carlo simulation. In each case, the 20 user locations are uniformly generated in desired cell. Based on the users positions, $\lambda_{ij}, i \in \{1,2\}, \mathrm{j} \in \{1,...,10\}$ are calculated. The position estimation deviation (σ_{ob}) is set to 10.

The user grouping is done based on the [20], which is explained in the system model section. For comparison, the performance of considering decoding order error in power allocation, two strategies are simulated. In the first one, the power is allocated with goal of rate maximizing based on [24]. In this paper, the maximum power of each group is derived based on the well-known Waterfilling form

$$\rho_n = \left[\frac{1}{\lambda} - \frac{1}{h_{2n}}\right]^+, \tag{18}$$

where $h_{in} = \frac{|\mathrm{d}_{in}^{-2}|}{\sigma^2}, i \in \{1,2\}$ which $h_{1n} > h_{2n}$. The parameter λ is derived based on the maximum power constraint which $\sum_{n=1}^{N} \rho_n \le P_{max}$.

The minimum rate quality constraint is considered for power allocation of each user in the second strategy, in which the rate is maximized. In this strategy, the power is allocated based on [24]

$$\rho_n = \left[\frac{1}{\lambda} - \frac{A_2}{h_{1n}} + \frac{A_2}{h_{2n}} - \frac{1}{h_{2n}}\right]^+, \tag{19}$$

where $A_2 = 2^{R_0}$. Note that in these strategies, the decoding order error is not considered at all, but the final rate is calculated based on Eq. (4).

In Figure.2 the average rate of each group of users for different strategies is shown. As expected, the proposed algorithm with goal of rate maximization by considering decoding order error of users achieves the highest rate performance.

In high SNR, the average achievable rate of different power allocation strategies with a rate maximization objective function converges. The reason is that the decoding order error probability in high SNR decreases. However, in low SNR, by considering decoding order error and allocating power based on it, the highest average achievable rate can be achieved.

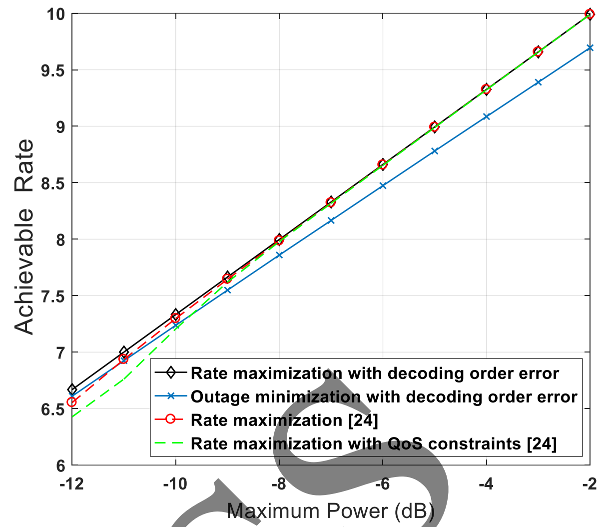

Fig 2. Average achievable rate of different power allocation strategies.

The difference of the proposed algorithm by considering decoding order error with different objective functions (rate maximization and outage probability minimization) is low in the low SNR region due to the low average achievable rate, which can be achieved by outage objective function. In high SNR, considering different objective functions is not negligible.

The outage probability performance of different power allocation strategies is shown in Figure 3. As expected, the outage probability of the power allocation with considering outage probability as an objective function is much lower than that of other power allocations.

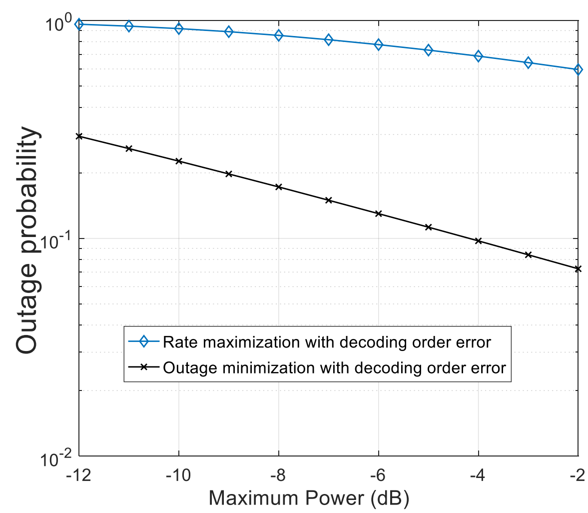

Fig 3. Outage probability of different power allocation strategies

5 Conclusion

In this paper, the decoding order error of NOMA users in multicarrier wireless communication system is considered in power allocation. Two different objective functions (rate and outage) are considered. The optimization problems are solved based on a convex optimization with Lagrangian multipliers and KKT approach. The performance of the proposed power allocation strategies is compared with together and with previous power allocation strategies proposed in other papers. The simulation results show that by considering decoding order error in resource allocation, better performance can be achieved compared to the previous power allocation strategies without considering this fact, which are a well-known water filling algorithm and power allocation that maximizes the rate with minimum rate constraint.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Baghani have done the innovation, problem solving, simulation, and article writing. Mr. Bahri has help in editing and revising the paper.

Informed Consent Statement

Not applicable.

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